EVALUATING THE PERFORMANCE OF PV MODULES IN BUILDINGS (BIPV/BAPV) AND THE SOILING EFFECT IN THE UAE DESERT SETTING

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ABSTRACT
This paper assesses the performance of photovoltaic (PV) technologies integrated into buildings in the desert climate and the factors that affect energy yield. Cadmium telluride (CdTe) and standard monocrystalline silicon (c-Si) modules were installed facing south, in the three more common tilt angles used in the Building Applied Photovoltaics (BAPV) and Building Integrated Photovoltaics (BIPV) applications at the Dubai latitude (90°, 25°, and 0°). We monitored the energy production, the temperature of the PV modules, irradiance on each tilt angle, and the meteorological parameters for a full year. We then calculated the performance ratio for the six modules to evaluate the different factors, including temperature and soiling losses, following IEC 61724-1. The 25° modules, usual PV rooftop angle, had the highest and more consistent energy yield throughout the year. Conversely, the energy yield of the 90° modules, typical angle for facades, vertical shading devices, and guardrails, had the lowest yield and showed wide variations. This is expected as the 90° angle is more affected by the seasonal changes of the solar altitude. The soiling losses on these modules were lower than 1%. However, at 0°, the soiling loss was more evident, with an average reduction of 10.79%. The c-Si module at 25° generated the highest normalized energy yield of 402.02 kW h/m^2, which was 23.5% more than that of CdTe module with the same tilt angle.
Keywords: BAPV, BIPV, building integrated, CdTe, c-Si, photovoltaics, soiling, tilt angle.

1 INTRODUCTION

In response to the current energy and environmental realities, the UAE government launched the national Energy Strategy 2050 which stated that by 2050, 44% of the energy demand should be supplied by clean energy sources [1]. The Dubai Energy Strategy 2050 is more ambitious, establishing that clean energy sources shall cover 75% of the electricity demand [2]. Due to the abundant solar resource and the reduction of photovoltaic (PV) system prices, solar energy plays an essential role in the region's energy transition [3]. On the other hand, Dubai buildings consume around 50%–70% of the total electricity output. Therefore, increasing the buildings' energy efficiency and promoting the installation of renewables in buildings are critical elements in the Dubai Demand Side Management (DSM) Strategy [2]. As part of its support to the DSM actions, the Dubai Electricity and Water Authority (DEWA) established the Distributed Renewable Resources Generation program. DEWA also launched the Shams Dubai initiative to activate the PV in buildings.

There are two ways of installing PVs in new and existing buildings, Building Applied Photovoltaics (BAPV) and Building Integrated Photovoltaics (BIPV). The BAPV modules generally are installed on the roof of the buildings, and their focus is to obtain the maximum energy production. Therefore, most of them are facing south, with the optimum tilt angle being 24° in the case of Dubai. BIPV solutions are multifunctional that, in addition to electricity generation, contribute to the building esthetic and perform as conventional building materials. They can be part of the roofs, opaque walls, glazing, and sun control [3], and the saving due to the replacement of building materials improves their life cycle cost.

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Furthermore, BIPV provides support to the energy network, can contribute to reduce the energy consumption in buildings, and can reduce the transportation losses in electricity grids [5]. In most of the cases, the orientation and the tilt angles of the BIPV are not optimum – 90° is the usual angle for facades, guardrails, sun control, and shading devices, and angles close to 0° are used in BIPV canopies, skylights, overhangs, and verandas.

In a desert context, the effects of the high temperatures and dust on the performance and lifetime of the PV modules present a concern for building owners and building professionals. Some research groups have studied how soiling affects the energy yield and efficiency of different types of modules in arid climates. One of these groups carried out 1-year monitoring of six types of PV technologies: monofacial and bifacial monocrystalline silicon, polycrystalline silicon, glass–glass poly-Si, copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) modules [6]. They installed the modules in a desert site, facing south, and with three different tilt angles (5°, 25°, and 90°), and found that the modules with 25° tilt had median monthly soiling losses between 2.76% and 6.15% and the modules with 5° tilt had losses between 5.09% and 8.15%. Additionally, their results revealed that the CdTe and CIGS modules showed high soiling losses. These researchers determined the energy losses associated with the high temperatures and soiling following the IEC 61724 standard. This standard includes procedures for acquiring various measurements, such as irradiation, ambient temperature, module temperature, wind speed, as well as electrical measurements. The IEC 61724 also defines several PV performance indicators such as overall system efficiency, performance ratio (PR), array yield, reference yield, final field, and capacity factor [7]. Therefore, researchers around the world follow this standard to evaluate the long-term performance of PV plants irrespective of size [8].

A performance assessment of rooftop crystalline silicon PV and comparison research demonstrated the high solar energy potential of Abu Dhabi [8]. PV systems in that city showed a higher energy output than the systems in Greece, Germany, Spain, and Italy. The high levels of irradiation in the UAE confirm the high viability of that country for the deployment of PV systems [9].

Usually, the factors that affect the efficiency of the BAPV and BIPV solutions are orientation, tilt angle, PV technology, and shading. In the UAE, high temperature, humidity, and soiling are also relevant factors to take into consideration. We conducted the present study intending to contribute to the understanding of the energy behavior of the PV in the buildings in the desert climates. With this purpose in mind, we selected two PV technologies suitable for BAPV and BIPV solutions and assessed the effects of high temperature, soiling, and tilt angles on their energy yield. We focus the present research work on PV in buildings with free air circulation all around, as rooftop installation, canopies, overhangs, verandas, guardrails, sun control, and shading devices.

2 METHODOLOGY

The PV experimental set-up was installed at the Outdoor Test Facilities (OTF) of the DEWA R&D Center. The DEWA R&D Center is part of the Mohammed Bin Rashid Al Maktoum Solar Park, Dubai, the UAE (23.4241° N, 53.8478° E). We selected two technologies for our study – standard monocrystalline silicon modules (c-Si), the prevalent technology for BAPV, and frameless thin-film modules (CdTe), a usual technology for BIPV.

The modules were placed facing south, the more favorable orientation in the Northern Hemisphere, and three tilt angles were utilized, 0°, 25°, and 90°. The 25° tilt angle, the optimum angle for the Dubai latitude, is ideal for the BAPV rooftop installations, as well as for BIPV slant roof canopies, verandas, and horizontal shading devices. The other two tilt angles

(0° and 90°) are more common in BIPV solutions. Building professionals use tilt angles equal to or close to 0° in flat canopies, overhangs, and horizontal shading elements and angles equal to or close to 90° in facades, vertical shading devices, and guardrails.

We installed the PV modules in an outdoor multi-tilt angle structure and monitored their output through an electronic load that performs the Maximum Power Point Tracking (MPPT) and logs the module's electrical parameters every 30 s. We collected the PV panels' temperature using PT100 thermal sensors in the back of each panel and measured the irradiance in each tilt angle using encapsulated crystalline silicon solar cell irradiance sensors. We collected other meteorological parameters (ambient horizontal global and direct radiation, temperature, humidity, wind directions, and velocity) from the DEWA R&D Center weather station, located next to the multi-tilt angle structure. We cleaned the modules on a monthly basis.

The duration of our study was 1 year, from March 2018 to February 2019. We used the data collected in this period to assess and compare the technologies and the factors that affected their performance, tilt angle, temperature, and soiling. To evaluate the performance of the PV modules and make the comparisons between them, we used the normalized energy yield, since the c-Si and the CdTe modules have different sizes. We estimated the losses due to module temperature and soiling following the IEC 61724 standard. Therefore, we calculated the temperature loss by comparing the PR of the modules with the temperature-corrected PR (tc-PR) to find the PR loss due to temperature. PR, expressed in eqn (1), is defined as the overall ratio of the actual measured energy yield of the PV system to the expected energy based on the efficiency of the module and the irradiation values.

$$PR = \left(\sum_k \frac{E_{out}}{P_o} \Big/ \sum_k \frac{H_i}{G_{i,ref}} \right) \tag{1}$$

where E_{out} is the energy output, P_o is the PV module-rated power at standard testing conditions (measured with indoor flash test), H_i is the plane-of-array (POA) irradiation for a reporting period k, and the reference irradiance $G_{i,ref}$ is the irradiance at which P_o is determined (i.e. 1000 W/m^2). We use a power rating temperature correction factor (C_k) in eqn (1) to get the tc-PR, as denoted in eqn (2):

$$C_K = 1 + \gamma \times \left(T_{mod,k} - 25°C \right) \tag{2}$$

where γ is the measured module's maximum power temperature coefficient and $T_{mod,k}$ is the module temperature (in °C) in time interval k. With the tc-PR values, which consider the temperature and irradiance variation, we were able to determine the daily soiling losses. Finally, we estimated the soiling losses by comparing the tc-PR values before and after each monthly cleaning event.

3 RESULTS AND DISCUSSION

The incident irradiance on the POA is critical to the performance of a PV system and is summarized in Table 1. The highest value corresponds to the modules with a tilt angle equal to 0°; the total irradiance in this plane was 2291.64 (kW h/m^2). The 0° and 90° planes received 9.8% and 38.3% less irradiance, respectively. The designers that look to obtain the maximum annual energy production with a fixed-angle PV installation in a building located in the UAE shall select the south orientation and a tilt angle equal to or close to 25°. We also monitored the energy produced by the c-Si and the CdTe modules and calculated their normalized energy yield, taking into consideration their different sizes (Table 2).

Table 1: PV modules specifications (as per the data sheet).

Technology	Area (m^2)	P_{stc} (Wp)	T_{coeff} (Pmpp)
c-Si	1.63	327.0	–0.35
CdTe	0.72	117.5	–0.28

Table 2: Total POA irradiation values for the test period.

Tilt angle	POA irradiance (kW h/m^2)	Relation between tilt angles
90°	1413.53	61.7%
25°	2291.64	100.0% (optimal)
0°	2068.09	90.2%

POA, plane-of-array.

When we compared the irradiance in the different planes with energy production (Tables 2 and 3), we found that the energy yield of both technologies, in general, followed the level of irradiance received in each plane. However, there is no perfect match. The differences indicate that other factors affected the performance of the modules. This led us to the analysis of the temperature of the modules and soiling.

The normalized monthly energy yield of the c-Si modules was higher than that of the CdTe modules throughout the year, irrespective to the tilt angle, as shown in Fig. 2. Also, regardless of the technology, the 25° modules (the usual PV rooftop angle) had the highest and more consistent energy yield. However, the 0° modules exceeded their energy yield in 3 months (May, June, and July). In these months, the sun reaches its higher altitude and its radiation is more perpendicular to the horizontal plane. Since the 0° tilt angle is closer to the optimum than the 90° tilt angle, the modules with that angle get a higher energy yield than the ones with 90° tilt (Table 3 and Fig. 2).

The energy yield of the 90° modules was the lowest. They showed wide variations throughout the test period. This angle was the most affected by the seasonal changes of the solar altitude. They had their lower energy production in May, June, and July and higher energy production in November, December, and January.

As part of the analysis of the effect of temperature on the energy production of the PV modules, we related the normalized energy (response variable) with the irradiance in each tilt

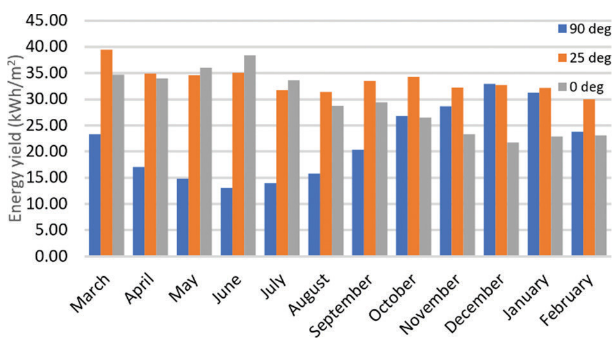

Figure 1: C-Si monthly energy yield normalized to module area (kW h/m^2). [Source: by authors]

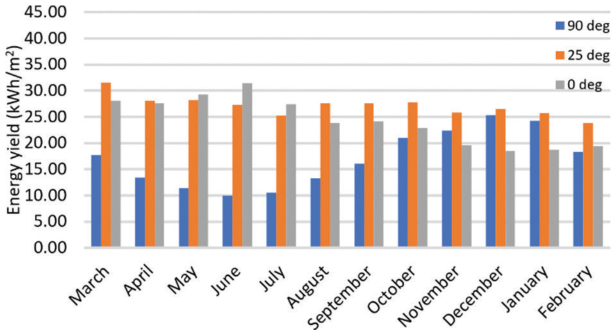

Figure 2: CdTe monthly energy yield normalized to module area (kW h/m^2).

Table 3: Annual energy yield normalized to the module's area (kW h/m^2).

Technology	Tilt angle	Normalized energy yield (kW h/m^2)	Relation between tilt angles
CdTe	90°	203.80	62.6%
	25°	325.41	100.0% (the best)
	0°	291.06	89.4%
c-Si	90°	261.66	64.95%
	25°	402.02	100.0% (the best)
	0°	352.33	87.65%

angle and PV panels' temperature (as two predictor variables). We made a graphical representation of these analyses using contour plots, which showed the production level in function of the irradiance and the PV panels' temperature. In Figs 2 and 3, we show a contour plot with the values of the energy yields reached with irradiance values equal to or greater than 2000 W h/m^2.

The PV modules' temperature is the result of a variety of factors, and the ambient temperature and solar radiation are the most important. For this reason, since the 25° modules received the highest levels of radiation, they were also the ones that experienced the highest temperature. In this tilt angle, the CdTe modules reached higher temperatures than the c-Si modules, at irradiance levels between 2000 and 3500 W h/m^2. The temperature levels of the 90° modules never reached the levels of the modules in other tilt angles, since the intensity of the solar radiation received by these modules was the lowest.

There were two common tendencies in both technologies regarding the tilt angle. First, the energy yield increased with the increment of irradiance, and second, the energy yield decreased with the increment of temperature. We found that the losses of performance due to the PV modules' temperature caused significant variability in energy yield with the same level of irradiance. Also, due to the high temperatures, the highest irradiance levels did not always result in the highest yield levels. As an example, when 25° c-Si modules received an irradiance of 4051 kW/h, their yield was 0.160 kW h/m^2 at a temperature of 61°C, 0.153 kW h/m^2 (11% more) at a temperature of 51°C, and 0.182 kW h/m^2 (14% more) at a temperature of 35°C. Similarly, when 25° CdTe modules received an irradiance of 4172 kW/h, their yield

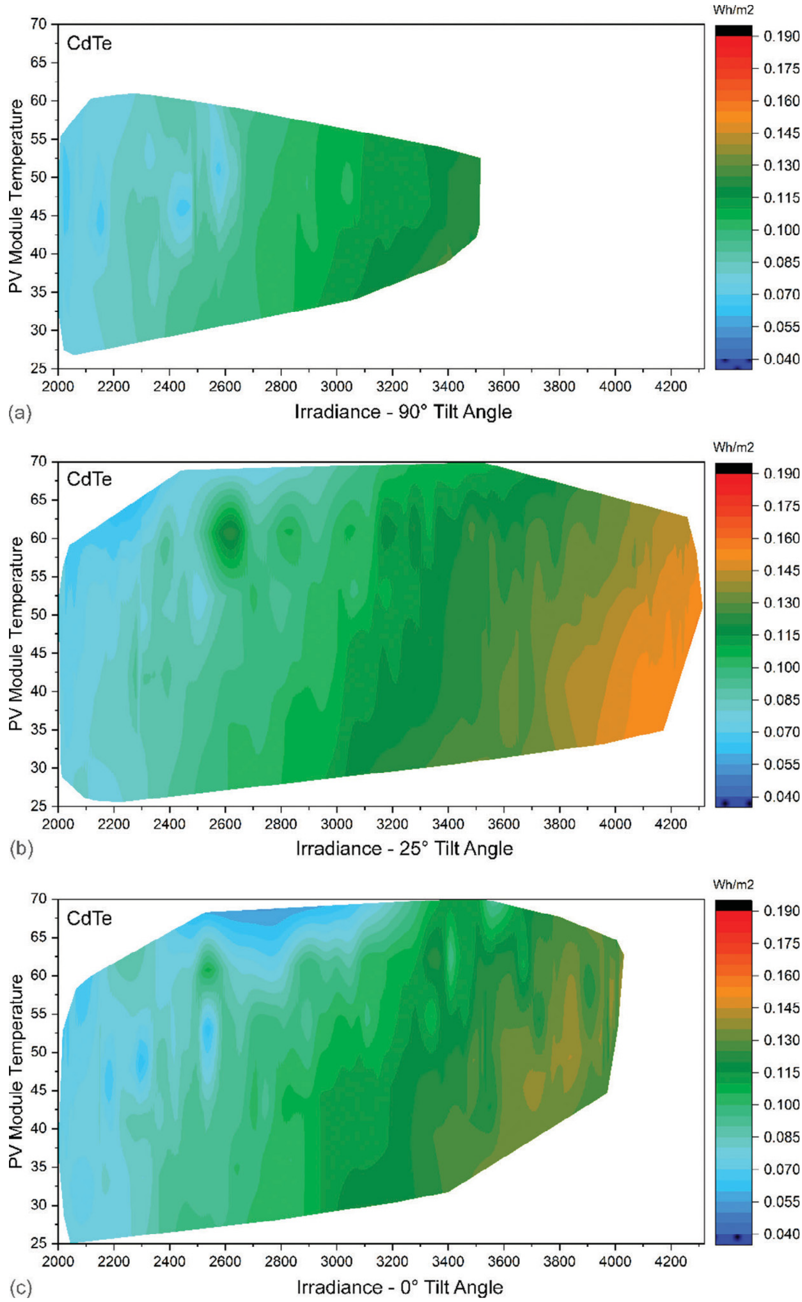

Figure 3: CdTe energy yield with respect to the irradiance and modules' temperature.

was 0.140 kW h/m^2 at a temperature of 58°C, 0.153 kW h/m^2 (9.3% more) at a temperature of 46°C, and 0.154 kW h/m^2 (10% more) at a temperature of 35°C.

We calculated the PV modules' temperature losses finding the difference between daily tc-PR and daily PR and have presented our findings in Fig. 4. The CdTe modules with a thermal coefficient lower than the c-SI (−0.35 vs. −0.28 Pmpp) had fewer temperature losses.

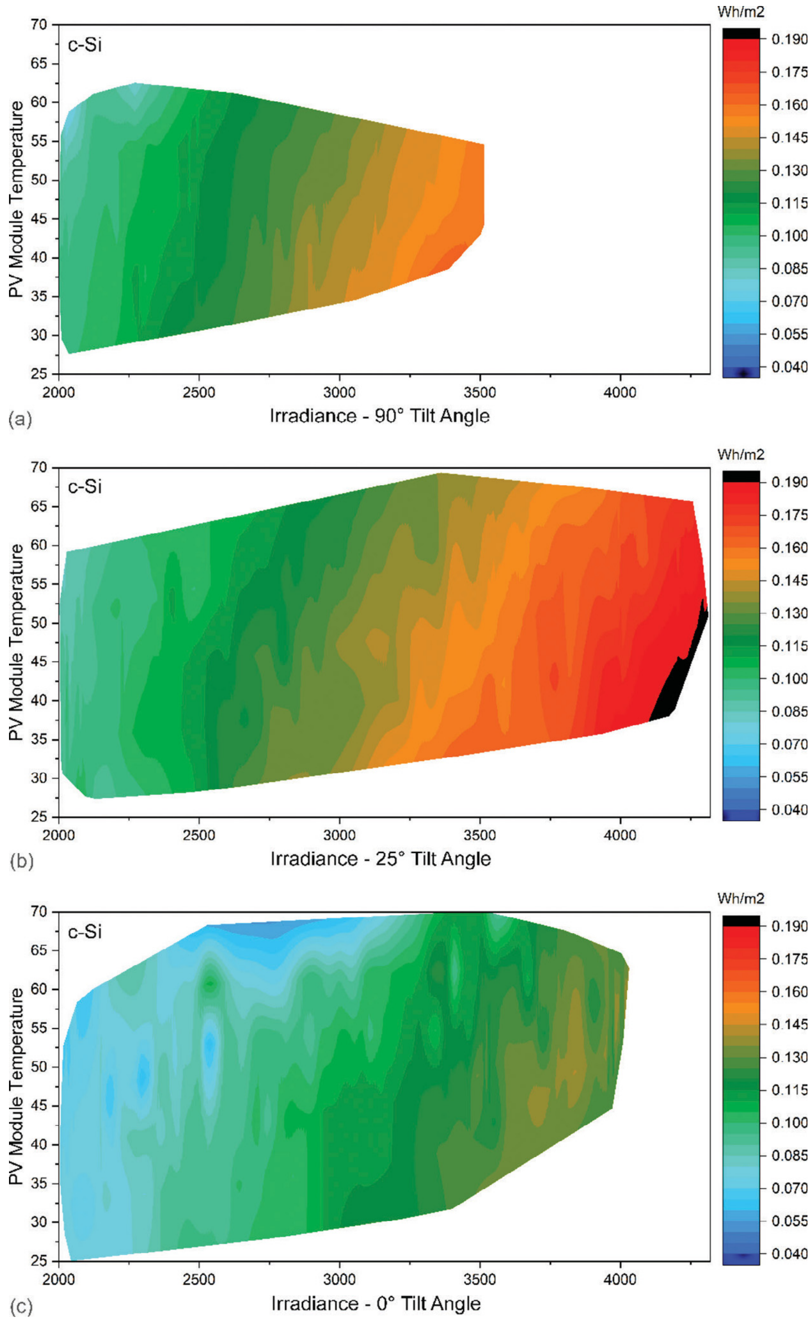

Figure 4: C-Si energy yield with respect to the irradiance and modules' temperature.

Several factors justify the 90° modules' low temperature losses. On one hand, the level of radiation received by 90° modules was lower than that in the other tilt angles, which resulted in low current and less overheating (Figs 2 and 3). And, on the other hand, the modules in this angle had better ventilation [6].

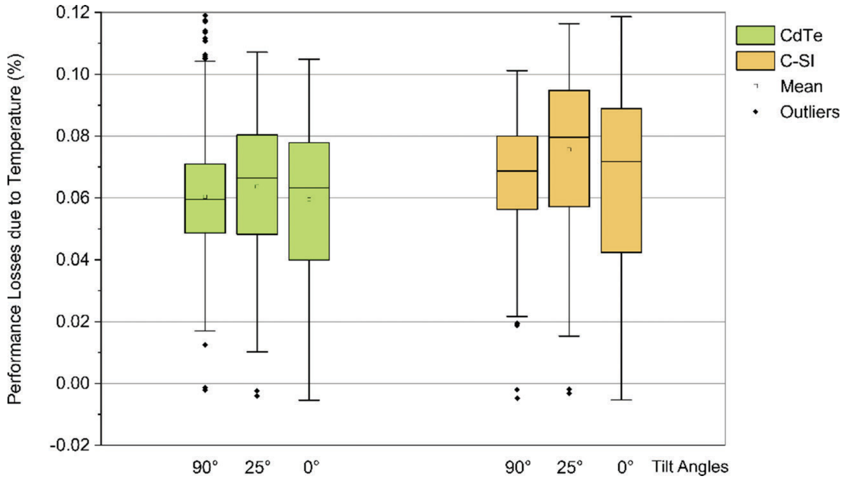

Figure 5: Performance loss due to temperature.
[Source: by authors]

We estimated the average monthly soiling loss by assessing the tc-PR increase after each cleaning event using the calculated tc-PR. The 90° modules presented negligible soiling losses, <1%. Conversely, the modules with lower tilt angles showed more significant soiling losses, 5.64% and 10.79% for the 25° and 0° modules, respectively. Therefore, the BAPV and BIPV solutions with low angles, as rooftop installations, canopies, and skylights, will require frequent cleaning to maintain their efficiency.

4 CONCLUSIONS

With the aim to contribute to the understanding of the factors that affect the energy performance of PV in buildings in the desert climates, we conducted an experimental research in Dubai using CdTe and c-Si modules, facing south and with three tilt angles (0°, 25°, and 90°). We analyzed the following factors in the study: PV technologies, tilt angles, PV modules' temperature, and soiling.

CdTe was the technology that was the least affected by high temperature due to its low temperature coefficient (–0.28 Pmpp). However, the c-Si modules had a higher normalized energy yield in all the tilt angles.

The 25° tilt angle modules had better performance, regardless of the technology, and showed a more consistent performance throughout the year. The 25° c-Si module generated the highest annual energy yield, 402.02 kW h/m^2. When the main objective of the BAPV or BIPV installation is to maximize energy production, the designer shall orient the PV elements facing south and select tilt angles equal to or close to 25°.

The 0° tilt angle modules showed a good performance; their energy production was between 10.6% and 12.4% less than the 25° modules. Also, they surpassed the energy production of the 25° modules in at least 3 months. However, they were the most affected by soiling losses (reduction of 10.79%). BIPV solutions in horizontal surfaces, as flat roof, skylight, and canopies, require frequent cleaning.

The 90° tilt angle modules had the lowest normalized energy yield, between 35% and 37% less than the 25° modules. They also showed high energy production variation throughout the test period. Their lower production was in the months May, June, and July. However, these modules were the least affected by the high temperature and soiling-related losses. BIPV modules installed as free-standing walls, guardrails, and vertical shading devices require less-frequent cleaning.

The focus of our study was the BAPV and BIPV solutions with free air circulation all around. Therefore, its findings might not apply to BAPV or BIPV installations with restricted or no ventilation.

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